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SSBUV AND NOAA-11 SBUV/2 SOLAR VARIABILITY MEASUREMENTS

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Summary: *The Shuttle SBUV (SSBUV) and NOAA-11 SBUV/2 instruments measured solar spectral UV irradiance during the maximum and declining phase of solar cycle 22. The SSBUV data accurately represent the absolute solar UV irradiance between 200–405 nm, and also show the long-term variations during eight flights between October 1989 and January 1996. These data have been used to correct long-term sensitivity changes in the NOAA-11 SBUV/2 data, which provide a near-daily record of solar UV variations over the 170–400 nm region between December 1988 and October 1994. The NOAA-11 data demonstrate the evolution of short-term solar UV activity during solar cycle 22.*

Keywords:

1. INTRODUCTION

In order to fully understand the origins of long-term trends in stratospheric ozone, spectral and temporal variations in solar irradiance must be characterized. The integrated (or total) solar irradiance is known to be constant to better than 0.3% over the 11-year solar cycle (*Lean, 1991*). Longward of approximately 290 nm, spectral solar irradiance can be observed from the ground, but instrumental limitations and atmospheric effects preclude measurement of predicted sub-1% variations over long time scales. The solar irradiance shortward of 290 nm in the ultraviolet (UV) region must be observed from space, using either short-term observations from recoverable instruments such as rockets and Space Shuttle flights, or long-term observations from satellite instruments. Rocket measurements have historically had significant uncertainties in absolute calibration (typically 10–20%) which have prevented the determination of long-term (i.e. solar cycle) changes from widely separated observations. Satellite data sets of solar UV irradiance typically suffer from rapid deterioration in instrument sensitivity with time, such that long-term trends are difficult to determine accurately.

In this paper, we describe the use of coincident Shuttle SBUV (SSBUV) data to create an accurate long-term solar UV irradiance data set from the NOAA-11 SBUV/2 instrument. The excellent absolute and relative accuracy of the SSBUV irradiances allows the NOAA-11 data to have a long-term uncertainty of less than ±1% at 400 nm over 5.5 years, and better than ±2% for all data longward of 200 nm. The combined SSBUV and NOAA-11 data indicate a long-term decrease of approximately 7% at 205 nm between the maximum of solar cycle 22 in 1989–1991 and the near-minimum conditions of October 1994, when NOAA-11 ceased solar measurements. NOAA-11 data also show the evolution of solar rotational activity in Cycle 22. Additional description of the long-term calibration of the NOAA-11 data can be found in *Cebula et al. (1998b)*.

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2. SSBUV DATA

The SBUV/2 instrument continuously measures backscattered terrestrial radiance at 12 discrete wavelengths between 252–340 nm, then measures solar irradiance once per week at the same wavelengths to produce spectral albedos which can be inverted to produce stratospheric ozone profiles (*Frederick et al., 1986*). Three SBUV/2 instruments have flown on NOAA TIROS spacecraft between 1985 and 1997 (NOAA-9, NOAA-11, NOAA-14), and three more launches are planned during the next decade. These instruments also make daily spectral scan measurements over the wavelength range 160–405 nm with a resolution of ~1.1 nm. The SSBUV instrument is the engineering model of the SBUV/2 instrument, which was modified to fly on the Space Shuttle to provide validation and long-term calibration (*Frederick et al., 1990*). SSBUV made eight flights between October 1989 and January 1996 (*Cebula et al., 1998a*). Because SSBUV was calibrated before, during, and after each mission, its solar irradiance data have significantly better accuracy than previous satellite instruments. Comparisons with coincident measurements in March 1992 from the UARS SUSIM and SOLSTICE satellite instruments (*Woods et al., 1996*) and the ATLAS SUSIM and SOLSPEC Shuttle instruments (*Cebula et al., 1996*) found that between 200–400 nm, the SSBUV data represented the mean solar UV irradiance measured by five independent instruments to approximately ±2.5% (2 σ) accuracy, with no spectral dependence. This is a considerable improvement over the ±10% inter-instrument differences shown by *Cebula and Hilsenrath (1992)*.

As noted previously, no measurable solar irradiance changes are expected at wavelengths longward of 300 nm on solar cycle timescales (*Lean, 1991*). The long-term accuracy of the SSBUV data is thus indicated graphically by Figure 1a, where the irradiance data from each flight, averaged over 380–390 nm and normalized to SSBUV-2, vary by < 1% over the first 7 flights. At shorter wavelengths, where long-term solar variations become significant, the SSBUV data show changes of 3–4% at 240–250 nm (Figure 1b) and 6–7% at 200–208 nm (Figure 1c) relative to the SSBUV-2 flight. The SSBUV-1 data were omitted from these figures because of calibration problems. The magnitude of solar variability at 205 nm is important in determining the external forcing of stratospheric photochemistry. Because the SSBUV data span only 3–8 days during each flight, a flight-averaged irradiance value can be affected by the phase of solar rotational modulation (*i.e.* peak or valley). Thus, the SSBUV data in Figure 1 incorporate both solar rotational variations and long-term solar change. We can use the daily NOAA-11 irradiance data to fully separate these two effects.

3. NOAA-11 DATA

NOAA-11 solar spectral irradiance measurements processed with full internal corrections exhibit significant long-term drifts at $\lambda < 300$ nm (up to 20% at 205 nm), because the SBUV/2 instrument is not capable of determining end-to-end calibration changes. Comparisons with coincident SSBUV observations provide a suitable reference source for evaluating and correcting these drifts (*Cebula et al., 1994*). Figure 2 shows the coincident spectral ratios between NOAA-11 and SSBUV data for the first seven SSBUV flights, averaged over the dates of each flight. All ratios have been normalized to remove the absolute spectral bias between NOAA-11 and SSBUV. Each ratio was fit spectrally with a smoothing spline function to remove residual effects of small wavelength registration errors. The degradation fit values from all flights at each wavelength were then fit with a quadratic function to determine the temporal dependence of the NOAA-11 correction. Examples of these data and the corresponding fits are shown in Figure 3.

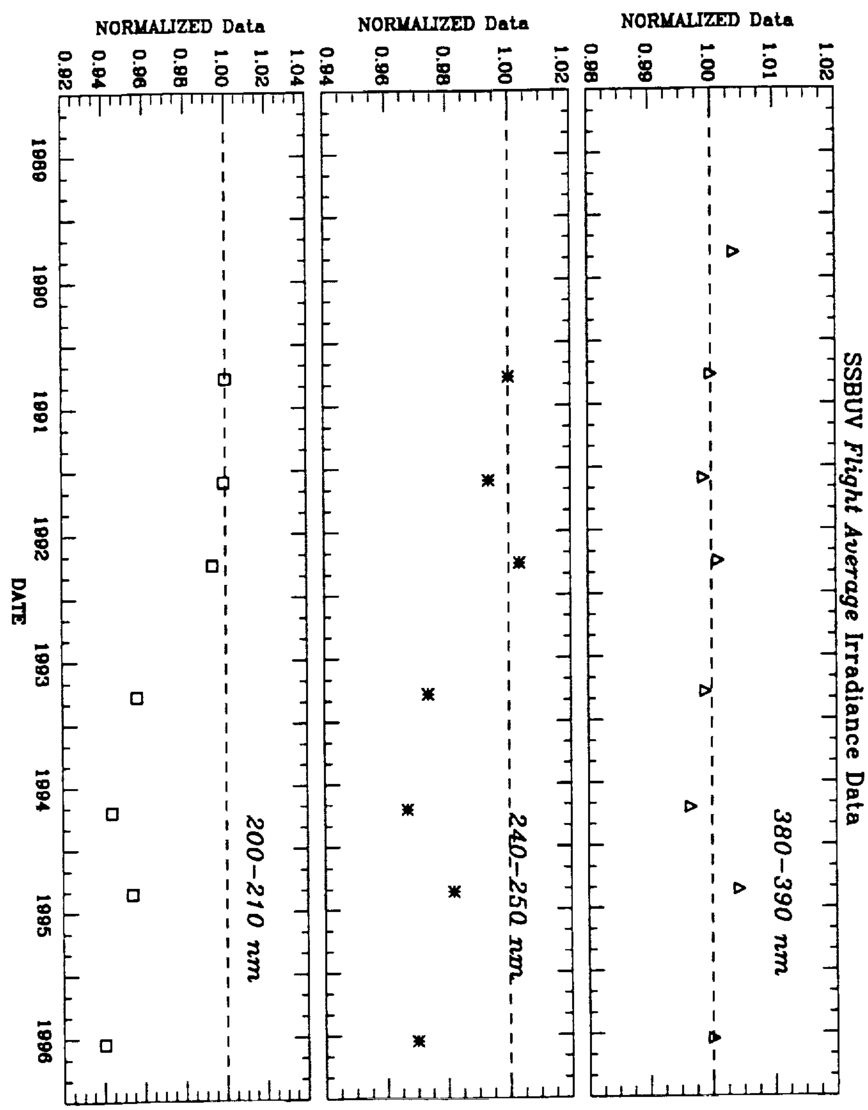

Fig. 1. Time series of SSBUV flight-averaged irradiance data: (a) 380-390 nm; (b) 240-250 nm; (c) 200-208 nm. All data have been normalized to the SSBUV-2 results.

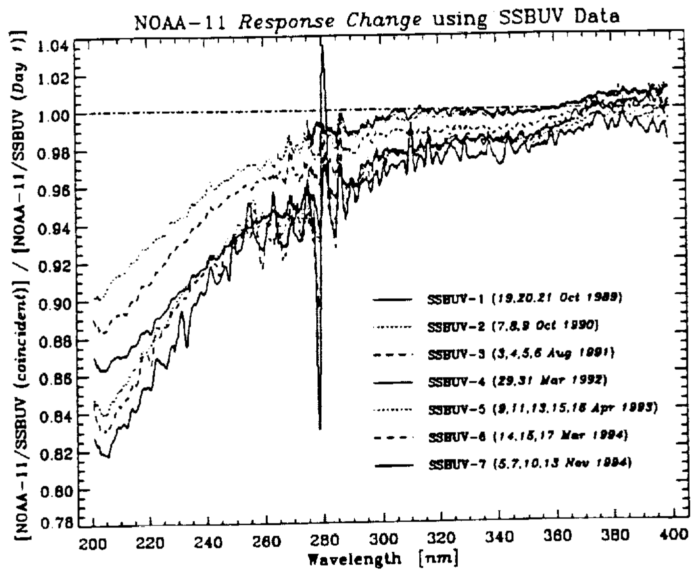

Fig. 2. Ratios of coincident NOAA-11 SBUV/2 and SSBUV spectra for the first seven SSBUV flights, normalized to remove absolute bias. Dates of SSBUV solar irradiance observations during each flight are listed.

After removing the SSBUV-based correction for sensitivity change, the NOAA-11 irradiance data give a good picture of solar UV variability during the maximum and declining phases of Cycle 22. Because coincident SSBUV data were used to correct NOAA-11 instrument changes, the derived long-term NOAA-11 solar variations will be approximately equal to the SSBUV results. The time series plot of the 380–390 nm band average in Figure 4a shows that the drift in the NOAA-11 data is less than ±1% over 5.5 years. At shorter wavelengths, such as the 240–250 nm band (Figure 4b), the corrected NOAA-11 data clearly show the extended activity maximum of solar cycle 22 during 1989–1991 and the sharp decline beginning in April 1992. Short-term variations due to rotational modulation are generally 2–3% peak-to-peak in this wavelength region. The heavy line in Figure 4b is a 27-day running average of the irradiance data, and indicates a long-term decrease in solar output of ~3% from late 1989 through October 1994. The 200–208 nm data, shown in Figure 4c, show similar temporal variations on both short and long time scales, with an increased amplitude because these data are taken shortward of the Al ionization edge. The long-term decrease implied by the 27-day average curve in this panel, which is effectively free of rotational modulation effects, is approximately 6%. This is consistent with the result found previously by SSBUV, showing that the SSBUV flight averages are not significantly impacted by rotational modulation effects. Recent calculations with 2-D atmospheric models using similar solar forcing find that the corresponding variation in globally averaged total ozone is approximately 1.5(±0.5)%

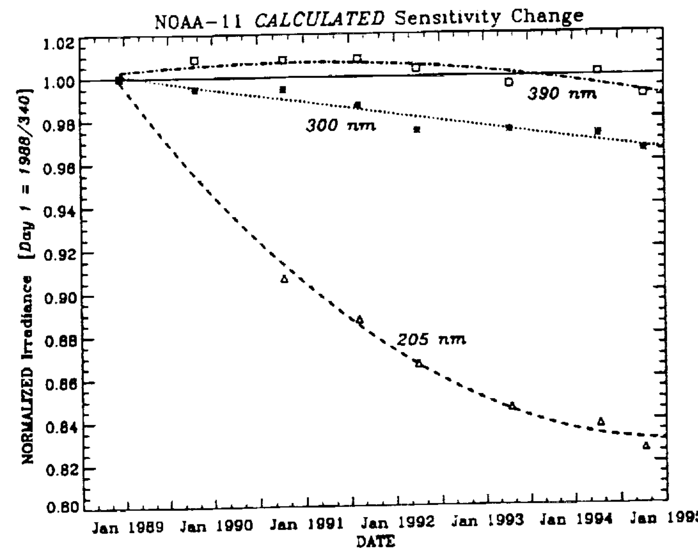

Fig. 3. NOAA-11 instrument sensitivity change at 205, 300, and 390 nm. Data values (symbols) are taken from Figure 2, and the curves are quadratic fits to each data set.

(*Fleming et al., 1995; Jackman et al., 1996*). The persistent solar rotational modulation in the NOAA-11 data, with a peak-to-peak amplitude of 4–6% during solar maximum and 2–3% during the declining phase of Cycle 22, can be studied further using statistical techniques.

4. PERIODOGRAM ANALYSIS

Time series such as the NOAA-11 irradiance data in Figure 4c are difficult to analyze with traditional power spectral analysis techniques, because they contain sizeable gaps which must be filled, thus possibly altering the statistical properties of the data set. The periodogram formulation presented by *Horne and Baliunas (1986)* successfully handles such data sets without filling or interpolation. Applying the periodogram technique to the 200–208 nm irradiance data produces the power spectrum shown in Figure 5, using 150 equally spaced frequencies corresponding to periods between 10 and 50 days. The dashed line indicates the power level at which the result is 99.9% statistically significant. We find two significant rotational peaks at approximately 26 and 29 days, and a peak at ~13.5 days which has less significance.

In order to understand the presence of multiple rotational periods, we can adapt the periodogram technique to characterize the evolution of solar activity. Following the method of *Bouwer (1992)*, we apply the periodogram to a 256-day window of data, then step the window through the data set at intervals of 64 days. The combined "dynamic power spectrum" results from all such periodograms are shown in Figure 6, where the lowest contour level represents 99.9% significance for these data. The strong rotational modulation signal (relative power > 40) during solar maximum has a 29-day period during early 1989, which shifts to a 26-day period by mid-1990, then drifts to a 27–28 day period by mid-1993. This evolution is the source of the double rotational peaks in Figure 5. The dynamic power spectrum also shows significant power with a period of ~13.5 days during late 1991 and early 1993. This represents true solar variability rather than aliasing of the 27-day rotational modulation, as shown by the time series in Figure 4c. An approximate 13-day period indicates the presence of active regions in opposing hemispheres simultaneously (*DeLand and Cebula, 1998*).

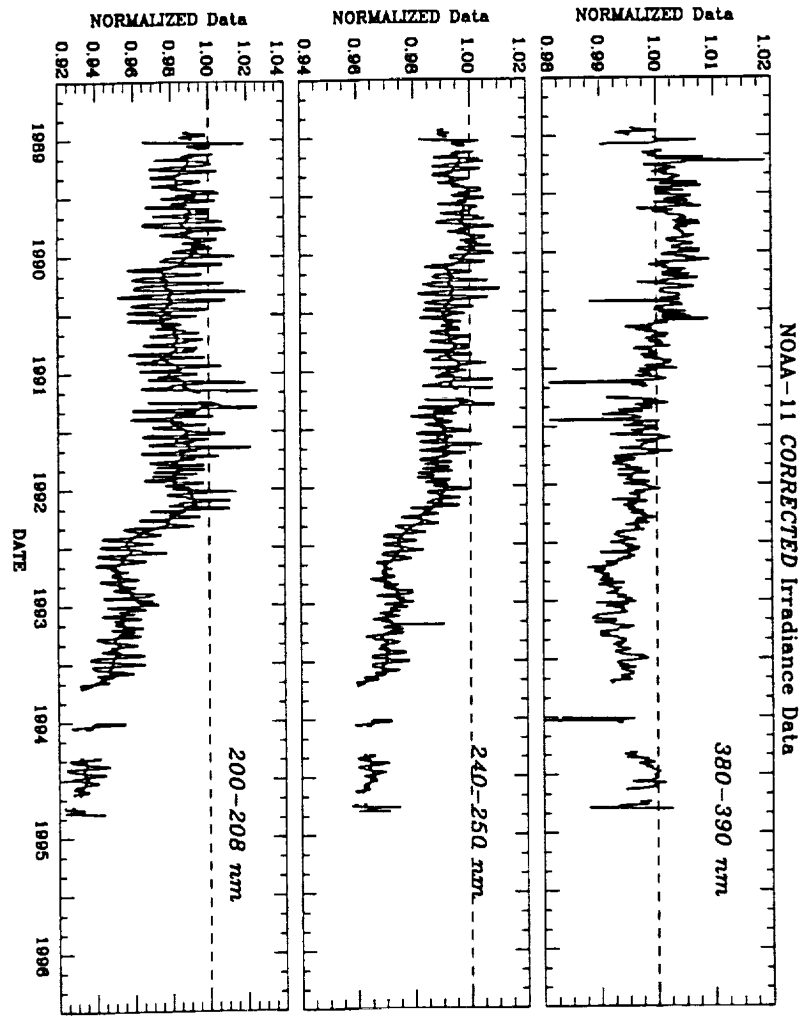

Fig. 4. Time series of NOAA-11 corrected irradiance data: (a) 380-390 nm; (b) 240-250 nm; (c) 200-208 nm. The heavy solid line in panels (b) and (c) is a 27-day running average of each data set.

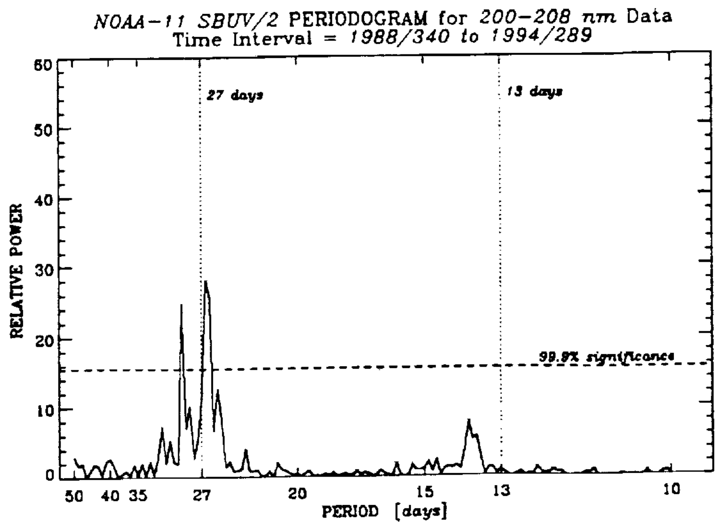

Fig. 5. Periodogram of NOAA-11 200–208 nm data for December 1988–October 1994. The dashed line denotes 99.9% statistical significance.

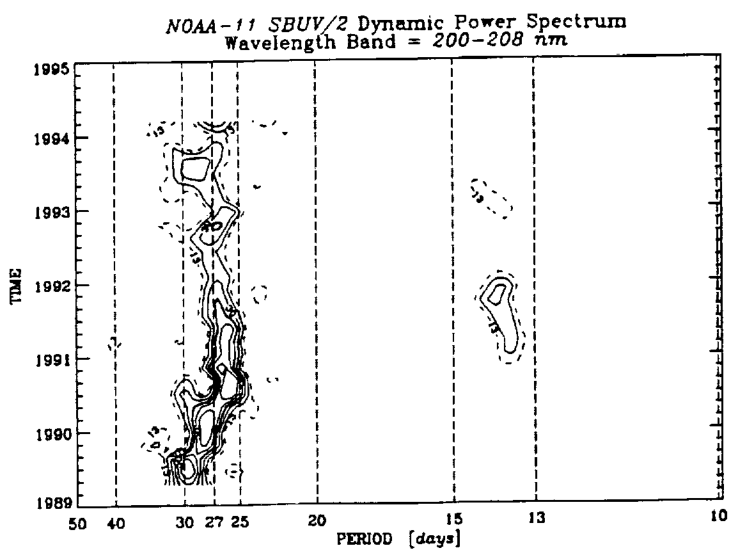

Fig. 6. Dynamic power spectrum of NOAA-11 200–208 nm irradiance data. Dashed contour represents 99.9% statistical significance; additional contours are in steps of 10, using the same scale as Figure 5.

5. CONCLUSION

Solar spectral irradiance data covering the wavelength range 170–405 nm from the SSBUV and NOAA-11 SBUV/2 instruments are now available for the period December 1988 to January 1996. The SSBUV data provide accurate absolute irradiances at 9–12 month intervals from the maximum of solar cycle 22 to near minimum. These data have also been used to correct long-term instrument sensitivity changes in the NOAA-11 data, which provide a near-daily record of solar UV irradiance from December 1988 to October 1994. The SSBUV-corrected NOAA-11 SBUV/2 data show a decrease of 6–7% in 205 nm irradiance during this period, which demonstrates the magnitude of solar forcing for stratospheric photochemistry. Model calculations with similar long-term solar variations give corresponding changes of approximately 1.5% in total ozone. The NOAA-11 data also show the evolution of solar rotational variations about their nominal 27-day period during solar cycle 22.

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